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# CIM-EARTH: Framework and Case Study

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# Contents

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**Abstract**

General equilibrium models have been used for decades to obtain insights into the economic implications of policies and decisions. Despite successes, however, these economic models have substantive limitations. Many of these limitations are due to computational and methodological constraints that can be overcome by leveraging recent advances in computer architecture, numerical methods, and economics research. Motivated by these considerations, we are developing a new modeling framework: the Community Integrated Model of Economic and Resource Trajectories for Humankind (CIM-EARTH). In this paper, we describe our framework and initial implementation and its application to a case study on carbon leakage, the impact of a unilateral carbon emissions policy on the global movement of industrial production capacity away from that region.

## 1 Introduction

Computable general equilibrium (CGE) models (Johansen, 1960; Robinson, 1991; Sue Wing, 2004) and their stochastic counterparts, dynamic stochastic general equilibrium models (del Negro and Schorfheide, 2003), form the backbone of policy analysis programs around the world and have been used for decades to obtain insights into the economic implications of policies (Bhattacharyya, 1996; Shoven and Whalley, 1984; de Melo, 1988). Hundreds of such models have been built (Devarajan and Robinson, 2002; Conrad, 2001) and used to explore such policy-relevant questions as the impact of new tax policies or increased fossil energy costs on consumers. These models also form a core component when studying the interaction between economic activity and the Earth system within integrated assessment models (Dowlatabadi and Morgan, 1993; Weyant, 2009).

Despite successes, however, these economic models have substantive limitations (Scrieciu, 2007). Models may not incorporate the industrial or process detail required to answer questions of interest; costs estimates from different models often differ considerably (Vuuren et al., 2009; Weyant, 1999, 2006; Friedlingstein et al., 2006; Lee, 2006); and little quantification of the uncertainty inherent in estimates is performed. Many limitations of current economic models are due to computational and methodological constraints that can be overcome by leveraging recent advances in computer architecture, numerical methods, and economics research. For example, contemporary models use mathematical formulations, numerical methods, and computer systems that restrict the size of the models that can be solved in a reasonable time, so that it is impractical to add detail such as increased industrial, geographic, or temporal resolution; capital and product vintages (Benhabib and Rustichini, 1991; Cadiou et al., 2003; Salo and Tahvonen, 2003); or overlapping

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generations (Auerbach and Kotlikoff, 1987). Understanding the distributional impacts of a carbon emission policy (Fullerton, 2009; Fullerton and Rogers, 1993), for example, requires one to represent the industries, regions, and overlapping generations for each income group that may be affected. Moreover, the interactions between policies that vary by region adds another level of complexity. More modern formulations and solvers and more powerful computer systems offer the potential to solve systems of equations that are several orders of magnitudes larger. Thus, we can in principle create models that encompass more of these details of importance to decision makers and characterize important aspects of uncertainty.

Motivated by these considerations, we are developing a new modeling framework: the Community Integrated Model of Economic and Resource Trajectories for Humankind (CIM-EARTH). Our goal is to facilitate and encourage the creation, execution, and testing of new economic models with significantly greater fidelity and sophistication than is the norm today. We envision the framework as combining (a) high-level programming that permits the convenient formulation of a wide range of models, (b) a flexible implementation that permits the efficient solution of these models using the most advanced numerical methods and high-performance computer systems, and (c) a suite of associated tools for parameter estimation and model evaluation.

We seek not only to provide access to better economic formulations and numerical methods but also to encourage the development and use of open models. Transparent policy studies, for example, require that software and data be *accessible* and *understandable*. If, in addition, we design software to be *modifiable* and *extensible*, then we also facilitate the reuse of methodologies and tools: a model produced by one researcher can be tested by others with different data and compared with other models and extended in new directions. In this way, the barriers to entry for newcomers to a research field can be reduced, and thus the diversity and quality of the ideas explored can increase. Therefore, we distribute our framework under an open-source license that permits others to read the software, modify it, and redistribute the modifications.

In this paper, we describe our framework and initial implementation and its application to a case study on carbon leakage, the impact of a unilateral carbon emissions policy on the global movement of industrial production capacity away from that region. Section 2 discusses our framework and its features, the foundation upon which our models are built. Section 3 details the model used for this case study. Section 4 presents results and the sensitivity of those results to the baseline assumptions. Scalar versions of the models used in the case studies are available from `www.cim-earth.org`.

# 2 CIM-EARTH Framework

To develop an accessible, understandable, modifiable, and extensible framework, our overall architecture uses a modular design; proven numerical libraries such as PATH (Dirkse and Ferris, 1995; Ferris and Munson, 1999, 2000), TAO (Benson et al., 2010), and PETSc (Balay et al., 1997); and a high-level specification language. In this section, we discuss the relevant parts of the CIM-EARTH framework for specifying and solving CGE models.

CGE models determine prices and quantities over time for commodities such that supply equals demand for each good (Ballard et al., 1985; Ginsburgh and Keyzer, 1997; Scarf and Shoven, 1984). Such models feature the following:

- Many *industries* that hire labor, rent capital, and buy inputs to produce outputs. Each industry chooses a feasible production schedule to maximize its profit.
- Many *consumers* that choose what to buy and how much to work subject to the constraint that purchases cannot exceed income. Each consumer chooses a feasible consumption schedule to maximize his utility function.
- Many *markets* where producers and consumers trade that set wage rates and commodity prices to clear the markets. If the price of a commodity is positive, then supply must equal demand.

Model instances are specified by defining the type of model (deterministic or stochastic, myopic or forward looking); the size of the model (regions, industries, consumers, and time periods); the details for the industries and consumers (production and utility functions and their nested structure), their parametrization (elasticities of substitution), and calibration data (expenditures and tax data for the base year); the

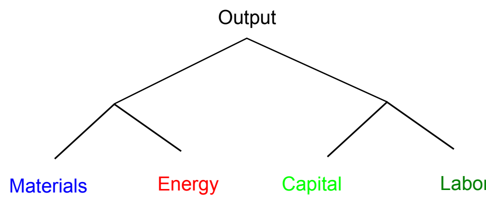


Figure 1: Basic nest for production function.

dynamic trajectories (land and labor endowments and capital accumulation); and the coupling with other system components.

The initial version of the CIM-EARTH framework has been implemented in the AMPL modeling language (Fourer et al., 2003). This language is convenient for expressing large optimization and complementarity problems using sets and algebraic constraints, provides access to a variety of commercial and academic numerical methods, and automatically computes the derivative information required by these methods to calculate a solution. We are currently developing a next-generation system that uses a domain-specific language to simplify model specification and target large parallel computers when solving them.

The primary challenge in developing such models is estimating the production and utility functions that characterize the physical and economic processes constraining the supply and demand decisions of industries and consumers. For our CGE models, we use nested constant elasticity of substitution (CES) production and utility functions in calibrated share form (Boehringer et al., 2003),

$$\mathbf{y} = \left( \sum_i \theta_i \left( \gamma_i \mathbf{x}_i \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}},$$

where $\mathbf{y}$ is the ratio between the output of the industry to a base year value, $\mathbf{x}_i$ are the ratios of the input commodities to their base year values, $\gamma_i$ are efficiency parameters that determine how effectively these factors can be used, $\theta_i$ are the share parameters with $\theta_i > 0$ and $\sum_i \theta_i = 1$, and $\sigma$ controls the degree to which the inputs can be substituted for one another. Our framework generates the special cases of Leontief ($\sigma = 0$) and Cobb-Douglas ($\sigma = 1$) functions automatically when used.

The nesting structure can be depicted graphically by a tree, with each node representing a production function with its own elasticity of substitution that aggregates the inputs from below into a commodity bundle. The root node represents the total output from the production process. Figure 1 show a simple case. In the CIM-EARTH framework, we add intermediate variables for the internal nodes, encode the individual functions by specifying the inputs and output, and reconstruct the tree from this information. Since the nesting structure is typically the same for each producer independent of the region in which they reside, we provide facilities to convey this information and reduce the amount of required coding.

Tables are used to convey the parametrization and calibration data. This data includes expenditures on inputs and tax information. The share parameters are automatically computed given the nesting structure of the production functions and the expenditure data for the base year. Also included is support for ad valorem and excise taxes, import and export duties, and endogenous tax rates, such as those encountered in cap-and-trade policies.

Once the problem structure and data are provided, we enter a processing phase to check consistency and make any necessary modifications. Consistency checks include testing the nesting structure to ensure it is a tree. Modifications are made to the tree structure, for example, to eliminate inputs that have zero expenditures or minuscule shares. The modifications are applied iteratively so that when all the leaves of a particular node are eliminated, that node is also eliminated. Such modifications are necessary to ensure that the nesting structure and provided data match.

After processing is complete, we have a set of constrained optimization problems for the producers and consumers and market clearing conditions. Because the optimization problems solved by the industries and consumers are convex in their own variables and satisfy a constraint qualification, we can replace each with an equivalent complementarity problem obtained from the first-order optimality conditions by adding

Table 1: Regions, industries, and factors for the CGE model used in the carbon leakage study. The industries are labeled by their production function structure: (A) agriculture, (E) extraction of fossil fuels, (M) manufacturing, (N) electricity generation, (P) petroleum refining, and (S) service industries.

| Regions | Industries | Factors |
|---|---|---|
| Canada (CAN) | Agriculture and Forestry (A) | Capital |
| Mexico (MEX) | Coal Extraction (E) | Labor |
| United States (USA) | Gas Extraction (E) | Land |
| Brazil (BRA) | Oil Extraction (E) | Natural Resources |
| Rest of Latin America (LAM) | Cement (M) | |
| Western Europe (WEU) | Chemicals (M) | |
| Rest of Europe (REU) | Nonferrous Metals (M) | |
| Middle East and North Africa (MNA) | Steel and Iron (M) | |
| Rest of Africa (AFR) | Other Manufacturing (M) | |
| China, Mongolia, and Koreas (CHK) | Electricity (N) | |
| India (IND) | Petroleum Refining (P) | |
| Japan (JAP) | Air Transport (S) | |
| Russia, Georgia, and Asiastan (RUS) | Land Transport (S) | |
| Rest of South Asia (SOA) | Sea Transport (S) | |
| Rest of Southeast Asia (SEA) | Government Services (S) | |
| Oceania (OCN) | Other Services (S) | |

Lagrange multipliers on the constraints. These optimality conditions in combination with the market clearing conditions form a square complementarity problem.

The simplest dynamic CGE models are *myopic*, in which the industries and consumers look only at their current state and do not consider the future. In this case, after the processing step, we loop over time and solve a complementarity problem for each time step with fixed trajectories for the factor endowments, efficiency parameters, and emission factors. Summary reports are written to user-defined files once the complementarity problem for each time step is solved.

The complementarity problem solved at each time step is automatically generated by the framework and is emitted in a scalar form so that it can be inspected. The complementarity problem is solved by applying a generalized Newton method, such as PATH (Dirkse and Ferris, 1995; Ferris and Munson, 1999, 2000). PATH is a sophisticated implementation of a Josephy-Newton method that solves a linear complementarity problem at each iteration using a variant of Lemke's method to obtain a direction and then searches along this direction to obtain sufficient decrease for the merit function.

# 3 Model Instance

We next provide a detailed discussion of the model instance implemented in the CIM-EARH framework used for the carbon leakage study. In particular, we specify the structure of the production functions, the data used to calibrate them, and the exogenous time-series forecasts of important economic drivers used to define a set of baseline scenarios.

## 3.1 Structure

Table 1 shows the regions, industries, and factors of the model instance used for studying carbon leakage. For each industry we indicate the structure of the production functions: (A) agriculture, (E) extraction of fossil fuels, (M) manufacturing, (N) electricity generation, (P) petroleum refining, and (S) service industries. This aggregation was chosen to contain more detailed resolution in the energy-intensive industries and in the industries that provide transport services to importers to move goods around the world since these industries would be most affected by a carbon tax or cap-and-trade program.

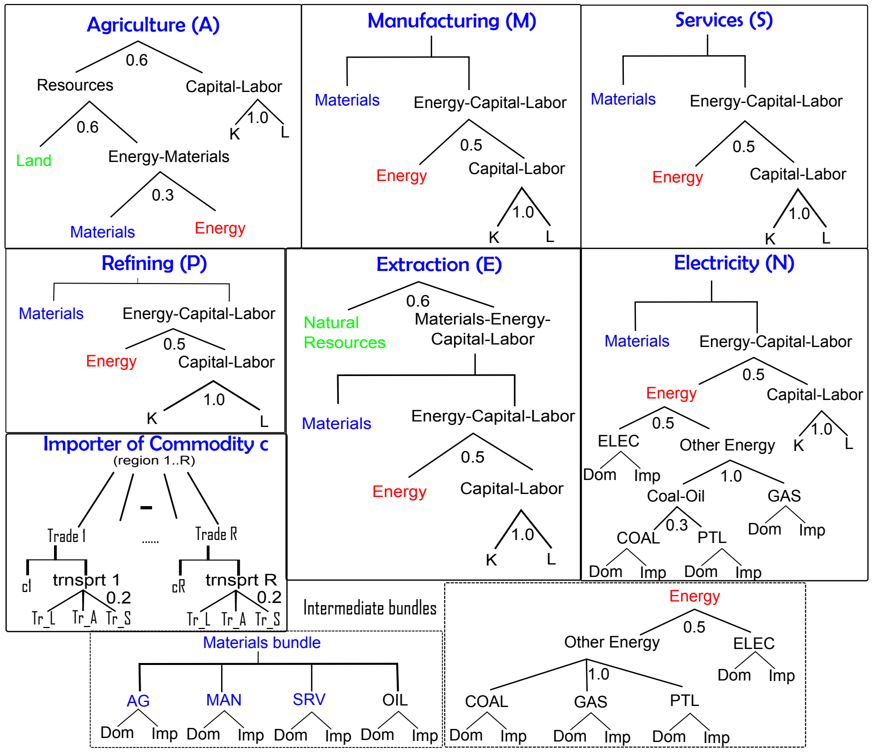


Figure 2: Structure of the production functions for the model instance used in the carbon leakage study. Each node represents a production function. Nodes with vertical line inputs use Leontief functions; the other nodes are labeled with their elasticities of substitution. The elasticities of substitution between domestic and imported commodities and the Armington international trade elasticities are given in Table 2.

The production functions in each region have the nested structure summarized in Figure 2 and are loosely based on those used in the EPPA model (Babiker et al., 2001). As before, each node represents a CES function aggregating the production factors below. The structure of the production functions for the importers of each commodity in each region is also provided. The capital goods industries aggregate materials using a single Leontief production function and do not demand fossil fuels, refined petroleum, electricity, or production factors; these capital goods are demanded only by consumers. We use elasticities of substitution taken from the CGE literature for the producers and consumers (Balistreri et al., 2003; Liu et al., 2004; Webster et al., 2008; Sokolov et al., 2009). We use the GTAP database for the base-year revenues and expenditures. In particular, the share parameters are calibrated with the GTAP v7 database of global expenditure values for 2004 (Gopalakrishnan and Walmsley, 2008).

Trade among regions is handled through importers of each commodity in each region. Importers are modeled like other producers using the nested CES production function shown in Figure 2. The elasticities of substitution between domestic and imported commodities and the Armington international trade elasticities used in the carbon leakage study are given in Table 2. We use a Leontief production function to aggregate between the imported good and the relevant total transport margin so that the amount of transport demanded scales with the amount of the good imported. We use three types of transportation: land transportation, including freight by trucks and pipelines; air transportation; and sea transportation. Since importers do not care about the origination of transport services, we model international transportation of each type as a homogeneous commodity having one global price. The homogeneous transportation service industries simply aggregate air, land, and sea transportation services from each region into a single commodity with a small elasticity of substitution, $\sigma = 0.2$. These homogeneous transportation services are used only for international trade; domestic transportation services are included in the materials nest of the other production functions.

Table 2: Elasticity of substitution parameters between domestic and imported commodities and the Armington international trade elasticities by industry for the CGE model used in the carbon leakage study. The industries are labeled by their production function structure: (A) agriculture, (E) extraction of fossil fuels, (M) manufacturing, (N) electricity generation, (P) petroleum refining, and (S) service industries.

| | **Elasticity of Substitution** | |
|---|---|---|
| **Industry** | Domestic/Import | Armington |
| Agriculture and Forestry (A) | 2.7 | 5.6 |
| Coal Extraction (E) | 3.0 | 6.1 |
| Gas Extraction (E) | 17.2 | 34.4 |
| Oil Extraction (E) | 5.2 | 10.4 |
| Cement (M) | 2.9 | 5.8 |
| Chemicals (M) | 3.3 | 6.6 |
| Nonferrous Metals (M) | 4.2 | 8.4 |
| Steel and Iron (M) | 3.0 | 5.9 |
| Other Manufacturing (M) | 3.4 | 7.2 |
| Electricity (N) | 2.8 | 5.6 |
| Petroleum Refining (P) | 2.1 | 4.2 |
| Air Transport (S) | 1.9 | 3.8 |
| Land Transport (S) | 1.9 | 3.8 |
| Sea Transport (S) | 1.9 | 3.8 |
| Government Services (S) | 1.9 | 3.8 |
| Other Services (S) | 1.9 | 3.8 |

This model does not contain a government consumer; it contains only a producer of government goods and services, which include defense, social security, health care, and education. Industries and consumers demand these government goods and services. The government producer is treated like any other producer and is subject to ad valorem and excise taxes. All taxes collected by a region are returned to consumers in that region.

Capital is specific to each region in the model instance. Within each region we use a perfectly fluid model of capital with a 4% yearly depreciation rate. To spur investment in capital, we use the standard practice in myopic CGE models in which investment contributes to consumer utility with the investment amount calibrated to historical data. Investment enters the consumer utility function in a Cobb-Douglas nest with the government services and consumption bundles, implying that a fixed share of consumer income in each year goes to government services, investment, and consumption. In particular, the consumer buys the output from an industry that produces capital goods. This industry demands material goods and services in order to produce the capital good but does *not* demand capital, labor, or energy. The change in the capital endowment in the next period relative to the amount in the base year is obtained from the dynamic equation

$$\mathbf{y}_{K,t+1} = (1-\delta)\mathbf{y}_{K,t} + \frac{\bar{x}_{I,0}}{\bar{y}_{K,0}}\mathbf{x}_{I,t},$$

where $\mathbf{y}_{K,t}$ is the change in capital endowment, $\mathbf{y}_{K,0} = 1$, $\mathbf{x}_{I,t}$ is the change in investment, and $\delta$ is the capital depreciation rate. The ratio of the base-year investment quantity $\bar{x}_{I,0}$ to the base-year capital stock $\bar{y}_{K,0}$ is available from the GTAP data.

## 3.2 Ensemble of Baseline Scenarios

We construct an ensemble of time-series forecasts for important economic drivers such as labor productivity and energy efficiency by extrapolation from historical data that are input into the model instance. By running the model instance for each set of forecasts without making any policy changes, we obtain an ensemble of baseline scenarios that can be compared to existing baseline scenarios from the literature. Moreover, by exploring policy scenarios over the range of baseline scenarios, we can determine the robustness of a policy to the assumptions used to produce the baseline scenario.

Our approach is different from much of the carbon leakage literature that typically starts from a reference baseline scenario, chooses a single set of time-series forecasts to replicate it, and then determines the change in outcome for a variety of policy scenarios, often without discussion of the scientific underpinnings of the baseline scenario or how it has been integrated into the model. While the trajectory of $CO_2$ emissions, for example, may match the EIA forecast, the parameters tuned to achieve this result and thus the business-as-usual assumptions are not described. This lack of documentation makes it difficult to compare results to the literature, since the results are reported relative to a single hypothetical baseline scenario for which the assumptions are not defined.

We now detail the construction of our ensemble of baseline scenarios, which are parametrized by national aggregate energy efficiency and labor productivity parameters. The space is reduced to two dimensions by assuming perfect correlations for the energy efficiency and labor productivity across regions. We then compare the results from our baseline scenarios to forecasts of emissions from the literature.

### 3.2.1 Fossil Extraction and Energy Efficiency

Crude fossil extraction, reserves, depletion, and backstops are important to understand how energy demand is met. Based on a simple fossil resource depletion model, we forecast Gaussian extraction curves fit to historical data for model regions independently, constrained to give future extraction equal to existing fossil reserves. This model combines forecasts of new reserve discoveries with advancing extraction technologies to predict the extraction curves. The remaining global conventional crude oil in our trajectory is about 1.6 trillion barrels (Tbbl), which is near the median of expert estimates in the standard literature. We have used simple, symmetric curves for these fits, implying smooth fall-off of extraction rates as reserves are depleted. The remaining global conventional gas in our trajectory is about 371 trillion $m^3$, which is near the 2007 WEC estimate of 386 trillion $m^3$. Forecasts for coal depletion are more ambiguous, with high estimated resources to proven reserves ratio and serious questions about what percentage will be technologically recoverable. The sum of coal reserves we use in our trajectory is 1.4 trillion tons of extractable coal resource. The estimate amounts to an assumption of only about 25% of the existing coal resources being ultimately recoverable, which is at the low end of estimated recoverable resources.

We incorporate an energy efficiency parameter into the industry production functions to model the efficiency by which energy is used. The inverse of regional industrial energy intensity is used as a proxy for the energy efficiency of industry. Historical industry gross domestic product is obtained from the UN database of national accounts, and historical industry energy use is obtained from the IEA World Energy Balance database. This data is used to calculate the year-over-year rate of change in industrial energy intensity. Rates for all regions in our model instance are available from 1972 to 2007. The data set is then truncated to eliminate the two largest positive and negative year-over-year swings to eliminate strong variations from one-time political events or economic crashes. The median baseline scenario then assumes that the average rate of change in energy intensity after 2008 is a weighted geometric mean of the historical rates.

The linear trend of the historical rate data advises the construction of the probability distribution for use in constructing the ensemble of baseline scenarios. For regions with a negative slope, $m$, in the linear trend, the distribution of the average rate of change in energy intensity for the forecast years is skewed lower by a multiple of the slope, currently $5m$. Positive slopes are treated similarly. The only exception is for the "Rest of Europe" region. Rapid development in energy efficiency in recent years as a result of technological improvements and economic shifts spurred by membership in the European Union implies rates of energy efficiency improvement that would surpass the gross energy efficiency levels forecast for the more developed parts of Europe, the United States, and Japan by 2030–2040. Since these efficiency levels seem highly unlikely, the implied shift in the linear trend is ignored for this region.

### 3.2.2 Population Growth and Labor Productivity

The other economic drivers we consider are population growth and labor productivity, which are combined to estimate the labor endowment in each region. We use gross population data from 1950 to 2008 with forecasts to 2050 from the 2008 United Nations population database (United Nations) and historical economic activity rates from 1980 to 2006 from the International Labor Organization (International Labor Organization, b) with projections to 2020 to determine the economically active segment of the population.

Labor productivity is chosen to match forecasts extrapolated from historical trends using data from the International Labor Organization Database of Key Indicators of the Labor Market (International Labor Organization, a). This database contains data for most countries spanning 1980 to 2005. For simplicity, we currently base labor productivity on the index of gross domestic product per person employed, even though productivity indices are available at sectoral resolution covering agriculture, forestry and fishing, manufacturing, trade, and transportation and communication for many countries. Forecasts are constructed in a manner similar to the energy efficiency parameter using a linearly weighted geometric mean.

### 3.2.3 Comparison to Emission Forecasts

We generated an ensemble of baseline scenarios containing 25 members by taking the cross product of five energy efficiency and five labor productivity parameters. Figures 3–5 compare the emissions generated by our model instance for each element of the baseline ensemble to historical data (Boden et al., 2009), 2005–2009 EIA reference case forecasts (United States Energy Information Agency), and 40 SRES scenarios from the IPCC AR4 (Nakicenovic et al., 2000). Only the 2005 EIA growth rate forecasts are shown in the left-hand plots to avoid clutter. The difference between our global emissions trajectories and the baseline forecasts produced by the EIA are due almost entirely to the divergence between our forecasts for China beyond 2011. Since our parameters are rooted in extrapolation from the historical record, it is not surprising that our trajectories miss the dramatic slowing in emissions for China forecast by the EIA. Our trends do show a similar decline in the rate of China's year-over-year emissions growth after 2011, but without the kink in both the 2005 and 2009 EIA forecasts. In particular, China's emissions growth rate drops from 6% in 2010 to less than 4% in 2011 in these EIA forecasts.

# 4 Carbon Leakage Study

In this policy study, we want to understand the impacts of a carbon tax on international trade, the extent to which carbon leakage limits global reductions in emissions, and the impact of border tax adjustments on reducing carbon leakage. The issue of carbon leakage has generated a significant literature, and a variety of approaches to estimation have produced a wide range of leakage estimates. Babiker (2005), for example, uses the EPPA model to predict leakage in excess of 100% in one scenario based on an assumption of increasing returns to scale. There exist far fewer estimates of the effects of border tax adjustments. Babiker and Rutherford (2005), for example, model the Kyoto Protocol and find substantial leakage and small effects from border tax adjustments.

We consider four policy scenarios in this study:

1. A business-as-usual scenario with no climate policy using the median baseline scenario described in Section 3.2 (BAU).

2. A policy scenario using the median baseline scenario in which each Annex B country taxes carbon at $105/tC (AB).

3. A policy scenario using the median baseline scenario in which each Annex B country taxes carbon and imposes a border tax adjustment on the estimated unpaid carbon content of imports from all non-Annex B countries at $105/tC (BTA).

4. A policy scenario using the median baseline scenario in which each Annex B country taxes carbon, assesses a border tax adjustment on the estimated total carbon content of all imports, and subsidizes all exports based on the total carbon content at $105/tC (BTAS).

We then report on the dependence of the emissions forecasts to the underlying baseline scenario assumptions. More policy scenarios can be found in Elliott et al. (2010).

Since carbon emissions are free in most of the world, data is typically unavailable for industry expenditures on carbon emissions in the base year, and we must instead compute the taxable carbon emissions. We measure the embedded emissions in each product by assuming conservation of emissions. In particular, the emissions content of the output is the sum of the emissions content of the constituent inputs and emissions generated

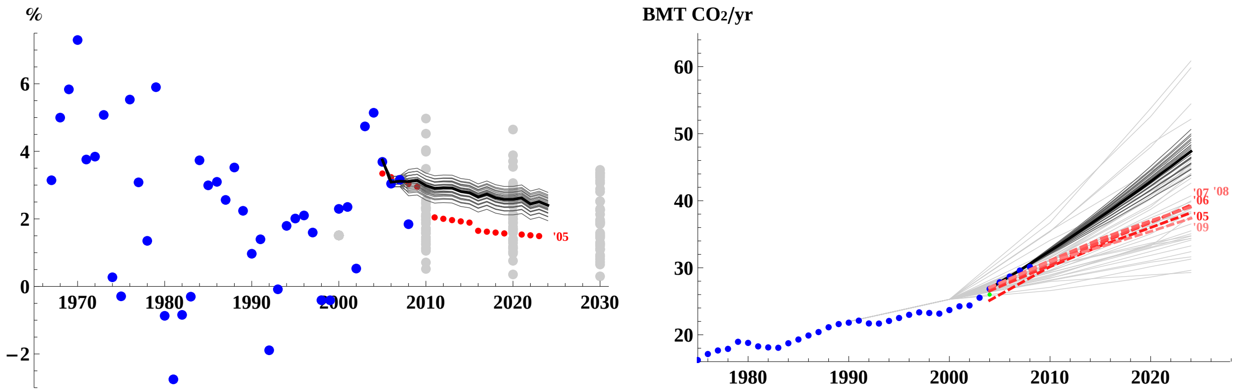


Figure 3: **Global $CO_2$ emissions**: comparison of historical data (blue), 2005–2009 EIA forecasts (red), SRES scenarios (light grey), and our ensemble of baseline scenarios (black) plotted as year-over-year growth rates (left) and as gross annual emissions (right).

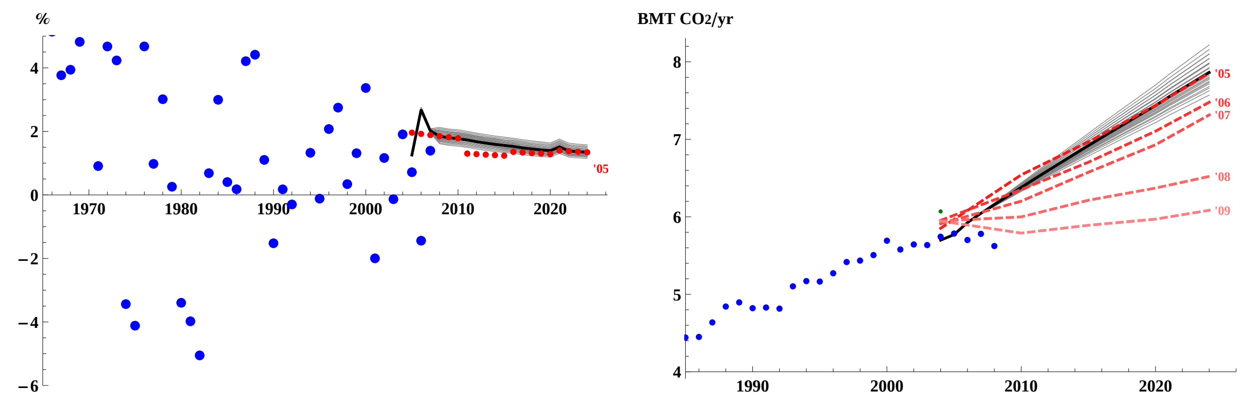


Figure 4: **USA $CO_2$ emissions**: comparison of historical data (blue), 2005–2009 EIA forecasts (red), and our ensemble of baseline scenarios (black and grey) plotted as year-over-year growth rates (left) and as gross annual emissions (right).

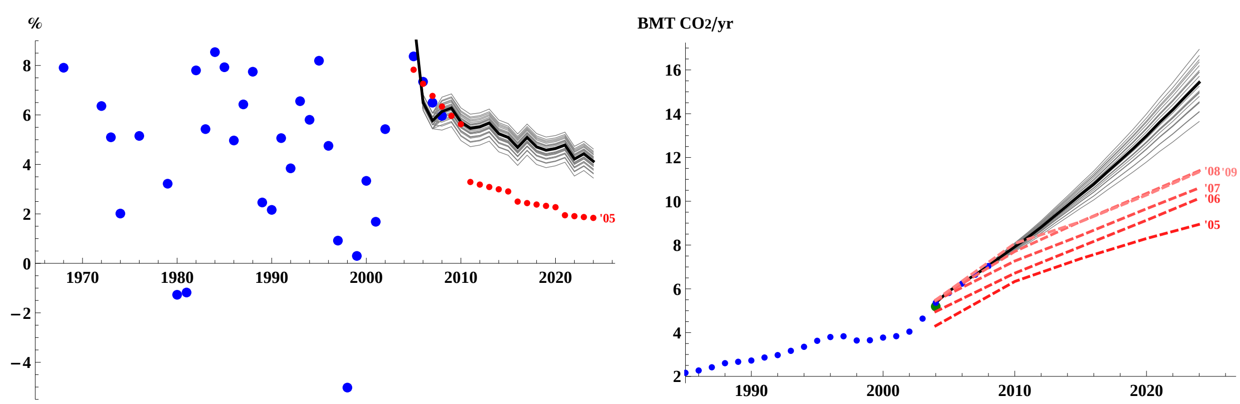


Figure 5: **CHK $CO_2$ emissions**: comparison of historical data (blue), 2005–2009 EIA forecasts (red), and our ensemble of baseline scenarios (black and grey) plotted as year-over-year growth rates (left) and as gross annual emissions (right).

during the production process from burning coal, natural gas, and oil. Specifically, the conservation of emissions is stated as

$$E_{j,t}\bar{y}_j\mathbf{y}_{j,t} = \sum_i (E_{i,t} + e_i^j)\bar{x}_i^j\mathbf{x}_{i,t}^j \,,$$

where $E_{j,t}$ is the total emissions content per unit of commodity $j$ in time $t$, $e_i^j$ is the emissions generated per unit from input commodity $i$ during the production process (the emissions factor), $\bar{x}_i^j$ is the base-year volume of commodity $i$ used in the production of commodity $j$, $\mathbf{x}_{i,t}^j$ is the change in demand relative to the base year for those inputs at time $t$, $\bar{y}_j$ is the base-year volume of commodity $j$ produced by the industry, and $\mathbf{y}_{j,t}$ is the change in output relative to the base year at time $t$.

The emission factors for new releases at the point of generation allow us to account for regional and industrial differentiation in different types of inputs and their emission rates. For example, the steel industry uses a large amount of coking coal with a high carbon content, while the electricity generated by coal-fired power plants typically comes from lignite with a low carbon content. Further, some industries, such as the chemicals and plastics industries, use inputs such as natural gas in the generation of their products but do not burn those fuels and hence have no new emissions generated from them. The computation of the total emissions content does, however, account for the emissions embedded in the natural gas they consume.

The new emissions generated by the producers from each input in the base year, $\bar{f}_i^j = e_i^j\bar{x}_i^j$, is obtained from the energy volume information in the GTAP-E data set (Burniaux and Truong, 2002). The embedded emissions expression $E_i\bar{x}_i^j$ is written in terms of generally unavailable base-year volume quantities. Therefore, we compute the total emissions budget for the industry measured in terms of the base-year quantities rather than compute the emissions content per commodity unit. In particular, we make the substitution

$$F_{j,t} = E_{j,t}\bar{y}_j$$

to obtain the equivalent system

$$F_{j,t}\mathbf{y}_{j,t} = \sum_i \left(F_{i,t}\frac{\bar{x}_i^j}{\bar{y}_i} + \bar{f}_i^j\right)\mathbf{x}_{i,t}^j \,.$$

In those cases where we know the base-year volume data, we directly compute the ratio of $\bar{x}_{i_r}^{j_r}$ to $\bar{y}_{i_r}$. In all other cases, we compute the ratio from available expenditure data,

$$\frac{\bar{x}_i^j}{\bar{y}_i} = \frac{\bar{p}_i\bar{x}_i^j}{\bar{p}_i\bar{y}_i} = \frac{\bar{e}_i^j}{\bar{r}_i} \equiv \Phi_i^j \,,$$

where the expenditure and revenue data for each industry, $\bar{e}_i^j$ and $\bar{r}_i$, respectively, are known from the base-year calibration data. If the volume and expenditure data are consistent, then the ratios computed from either method will be identical. We then obtain the system of equations

$$F_{j,t}\mathbf{y}_{j,t} = \sum_i \left(F_{i,t}\Phi_i^j + \bar{f}_i^j\right)\mathbf{x}_{i,t}^j \,. \qquad (1)$$

We estimate the emissions content $F$ for each industry by solving the system of equations (1) for given $\Phi$, $\bar{f}$, $\mathbf{x}$, and $\mathbf{y}$. These amounts are then used to determine the carbon taxes on imports and subsidies on exports for the border tax adjustments. However, this system has more variables than equations because of the land, labor, and capital factors. In our model, we ignore the contribution of these factors to the emissions by fixing their amounts to zero. We are then left with a square system of equations that can be solved. For all of our scenarios, we solve the CGE model instance for the given year using the current emissions estimate, compute the emissions for the next year using the output, and increment the time. That is, we use the emissions estimate from the previous year to determine the border tax adjustments. For the scenario where we compute only unpaid emissions content, we simply set $\bar{f}_i^j = 0$ for the producers in the Annex B countries. We use the full emissions data when computing the total emissions for the other scenarios.

To present the results, we define a carbon flow matrix that shows the emissions in each region. We fix total produced emissions by calculating the fossil fuel consumption in each region, estimate the export emissions flows, and assign the remaining emissions to local consumption. We aggregate from 16 regions to 8 regions in the carbon flow tables for readability. Annex B regions are largely left disaggregated; JAP and

Table 3: Fossil fuel $CO_2$ accounting in 2004 for the BAU scenario in millions of tonnes, showing carbon producers (or exporters) on the vertical and carbon consumers (or importers) on the horizontal. The diagonal gives domestic consumption.

| BAU | Annex B | | | | | Non Annex B | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2004 | USA | EU | RUS | JAZ | CAN | CHK | LAM | ROW | Prod. |
| USA | 5012.3 | 279.8 | 7.4 | 94.8 | 177.4 | 109.1 | 209.1 | 112.3 | 6002.2 |
| EU | 303.1 | 3928.1 | 62.7 | 72.3 | 28.3 | 96.3 | 65.9 | 306.5 | 4863.2 |
| RUS | 70.7 | 408.3 | 1468.3 | 22.4 | 3.3 | 82.6 | 22.0 | 100.3 | 2177.8 |
| JAZ | 83.7 | 81.6 | 3.1 | 1146.5 | 7.6 | 160.2 | 12.5 | 97.7 | 1593.0 |
| CAN | 247.7 | 32.7 | 0.8 | 8.6 | 223.0 | 11.5 | 8.4 | 10.0 | 542.8 |
| CHK | 576.7 | 586.6 | 32.0 | 390.5 | 49.9 | 3679.3 | 103.3 | 478.4 | 5896.8 |
| LAM | 293.1 | 121.8 | 5.5 | 18.4 | 15.9 | 36.2 | 955.8 | 40.2 | 1487.0 |
| ROW | 300.2 | 657.2 | 30.6 | 289.3 | 20.5 | 375.8 | 55.3 | 3199.1 | 4928.0 |
| Cons. | 6887.5 | 6096.2 | 1610.4 | 2042.9 | 526.0 | 4550.9 | 1432.3 | 4344.5 | 27490.7 |

AUS are aggregated to JAZ, and WEU and REU are aggregated to EU. For non-Annex B regions, we leave the CHK region intact, aggregate all of Latin America, and aggregate all other regions – Africa and Central, South and South East Asia – as ROW.

The carbon flow matrix for the BAU scenario in the 2004 base year is shown in Table 3. The diagonal value indicates the emissions generated from domestic production and consumption. The off-diagonal entries indicate the emissions embedded in imports and exports. The difference between the row sum and the column sum determines whether the region is a net importer or exporter of emissions. In particular, USA is a net importer of emissions while CHK is a net exporter. The lower-right corner indicates global emissions. For the 2004 base year, global emissions are in good agreement with the emissions database produced by GTAP Lee (2009) from the IEA energy database and with the CDIAC National Fossil-Fuel $CO_2$ Emissions database Boden et al. (2009).

Table 4 shows the carbon flow matrix for the AB scenario with a carbon price of 105\$/tC (AB-105) relative to the BAU scenario. The upper-left block of the matrix shows decreased trade among the Annex B regions, while the lower-right block shows increased trade among the non-Annex B regions. Increases in imports of carbon from the non-Annex B regions due to carbon leakage are shown in the lower-left block. In particular, the carbon consumption for each Annex B region (direct and virtual) falls much more slowly than their carbon production because of leakage. Depending on how the goal for an emissions target is defined, this fact can change the necessary carbon price by as much as 15–20%.

Table 4: Percent change in emissions in 2020 for the AB scenario, a scenario with a constant 105\$/tC (USD per tonne carbon) tax levied in all Annex B countries starting in 2012, relative to the BAU scenario. The largest gross changes ($|\Delta E| \geq 50$ $MtCO_2$) are shown bolded, and the smallest ($|\Delta E| \leq 10$ $MtCO_2$) are shown faded.

| AB-105 | Annex B | | | | | Non Annex B | | | |
|---|---|---|---|---|---|---|---|---|---|
| vs. BAU | USA | EU | RUS | JAZ | CAN | CHK | LAM | ROW | Prod. |
| USA | **-27.2** | **-20.0** | -22.5 | -27.0 | -21.7 | **-25.4** | **-30.0** | -29.6 | **-26.8** |
| EU | **-23.6** | **-23.3** | -19.6 | -18.3 | -17.7 | -21.6 | -23.4 | **-28.2** | **-23.5** |
| RUS | **-38.0** | **-33.9** | **-29.4** | -34.6 | -34.0 | **-37.6** | -40.0 | **-35.6** | **-31.5** |
| JAZ | -14.2 | -14.4 | -17.2 | **-32.9** | -18.8 | **-22.3** | -19.3 | -25.0 | **-28.8** |
| CAN | **-20.8** | -18.6 | -16.2 | -19.0 | **-26.1** | -19.8 | -20.1 | -20.7 | **-22.8** |
| CHK | 1.1 | 1.8 | 2.0 | 3.0 | 2.0 | **2.8** | 2.3 | 1.3 | **2.4** |
| LAM | **24.7** | 14.0 | 47.7 | 4.3 | 25.9 | 3.0 | **6.6** | 5.4 | **10.7** |
| ROW | 8.0 | **12.8** | 18.5 | **15.2** | 8.4 | **6.2** | 9.6 | **4.7** | **6.6** |
| Cons. | **-19.4** | **-15.1** | **-26.7** | **-15.6** | **-17.0** | 0.3 | -1.0 | -0.1 | **-9.9** |

The addition of an import tax on carbon content in the BTA scenario has a small, but not insubstantial

Table 5: Percent change in emissions in 2020 for the BTA scenario, a scenario with a constant 105$/tC (USD per tonne carbon) tax levied in all Annex B countries and on the unpaid emissions embedded in imports from non-Annex B countries starting in 2012, relative to the BAU scenario.

| BTA-105 | Annex B | | | | | Non Annex B | | | |
|---|---|---|---|---|---|---|---|---|---|
| vs. BAU | USA | EU | RUS | JAZ | CAN | CHK | LAM | ROW | Prod. |
| USA | **-25.5** | **-18.1** | -20.7 | -16.4 | -19.2 | **-35.8** | **-36.2** | **-37.7** | **-25.8** |
| EU | -12.4 | **-19.9** | -17.6 | -14.9 | -14.3 | **-33.4** | -31.5 | **-36.6** | **-21.0** |
| RUS | -27.8 | **-30.0** | **-27.8** | -24.2 | -30.9 | **-49.9** | -51.6 | **-45.1** | **-30.3** |
| JAZ | -12.8 | -15.0 | -17.0 | **-25.8** | -18.1 | **-35.5** | -28.0 | -35.8 | **-26.7** |
| CAN | -14.8 | -18.6 | -13.7 | -16.7 | **-22.3** | -32.1 | -29.1 | -30.7 | **-19.8** |
| CHK | **-9.4** | **-10.5** | -12.1 | **-11.1** | -11.9 | **3.8** | 13.6 | **8.6** | **0.9** |
| LAM | -8.5 | -4.0 | 10.6 | -2.7 | -4.6 | 3.6 | **5.7** | 7.3 | **2.7** |
| ROW | -5.2 | **-6.9** | -9.2 | -8.1 | -6.2 | **8.0** | 16.6 | **4.6** | **2.8** |
| Cons. | **-21.1** | **-17.3** | **-26.5** | **-18.8** | **-18.6** | **0.5** | -0.8 | 0.2 | **-10.7** |

Table 6: Percent change in emissions in 2020 for the BTAS scenario, a scenario with a constant 105$/tC (USD per tonne carbon) tax levied in all Annex B countries and on the total emissions embedded in all imports with subsidies on all exports for the carbon taxes levied starting in 2012, relative to the BAU scenario.

| BTAS-105 | Annex B | | | | | Non Annex B | | | |
|---|---|---|---|---|---|---|---|---|---|
| vs. BAU | USA | EU | RUS | JAZ | CAN | CHK | LAM | ROW | Prod. |
| USA | **-25.6** | **-19.0** | -21.4 | -18.7 | -20.4 | **-23.9** | -16.9 | -22.0 | **-24.7** |
| EU | -13.7 | **-20.2** | -17.5 | -15.9 | -15.6 | -25.8 | -21.8 | **-23.1** | **-20.1** |
| RUS | -31.8 | **-32.6** | **-30.3** | -29.0 | -33.5 | -16.4 | -18.9 | -12.4 | **-28.7** |
| JAZ | -13.4 | -15.9 | -16.5 | **-26.3** | -18.8 | **-25.8** | -20.4 | -27.7 | **-25.1** |
| CAN | -15.6 | -19.1 | -13.5 | -18.2 | **-23.1** | -24.7 | -20.8 | -22.1 | **-19.6** |
| CHK | **-8.0** | **-8.9** | -10.0 | **-9.9** | -10.3 | **3.1** | 9.4 | **5.6** | 0.3 |
| LAM | -9.9 | -2.7 | 15.5 | -1.3 | -2.8 | -1.0 | **4.0** | 0.6 | 0.5 |
| ROW | -4.1 | -5.8 | -6.4 | -7.1 | -4.5 | 1.8 | 7.9 | **3.2** | **1.2** |
| Cons. | **-20.8** | **-17.4** | **-28.5** | **-18.4** | **-18.6** | **0.5** | 0.2 | 0.5 | **-10.8** |

effect on global emissions. Where the emissions are generated changes substantially from the AB scenario, as shown in Table 5. In particular, there is increased trade between the Annex B countries, causing them to increase their emissions generated. There is also some increased trade between non-Annex B countries. However, the off-diagonal blocks show decreased trade between Annex B and non-Annex B countries. The net result is a small reduction in global emissions.

The results when adding export subsidies on the carbon taxes paid are shown in Table 6. These subsidies reduce the amount of trade between non-Annex B countries and hence their emissions, but the Annex B countries increase production for exports to non-Annex B countries. The result is a small further reduction in global emissions, but the producers in Annex B countries are better off.

We now determine how strongly the gross emissions forecasts from our model instance depend on the assumptions of the underlying baseline scenario. Even if the emissions output relative to the baseline scenario is the same for two different scenarios, the gross emissions relevant for policy evaluation are rarely the same. The stated USA emissions target under the nonbinding international agreement from the December 2009 Copenhagen meeting, for example, was a 17% reduction from 2005 emissions levels by 2020. CGE models can say little about achieving these absolute policy targets without an explicit treatment of the range of baseline scenarios that underlie any forecast.

To complete this analysis, we ran our model instance using the parameters in each of the 25 baseline scenarios outlined in Section 3.2. Figure 6 compares the AB-105 policy scenario on the reduction in USA emissions, the reduction in total emissions from Annex B countries, and the total increase in emissions from non-Annex B countries in 2020 across the range of baseline scenarios. Each connected line is a subsample with a fixed value of the labor productivity parameter and varying energy efficiency parameter. The figure presents the reduction in the percent change in emissions relative to the baselines and the gross emissions.

The relative impact of the policy on total emissions in the Annex B countries appears to be fairly robust against varying assumptions on the labor productivity growth rate when measured in gross terms and less robust to varying assumptions in the energy efficiency growth rate. The USA is a notable exception; emissions reductions in this region are more sensitive to the assumptions on labor productivity than on energy efficiency, with the same overall trend regarding marginally more emissions reductions in baseline scenarios with higher emissions. Measured in percent terms, the ensemble of baseline scenarios studied gives a sensitivity range for gross emissions of about 1%. We note that our study is over a very compact ensemble relative to the range implied by the distribution of EIA forecasts over the past five years shown in Figure 4.

Increased emissions in the non-Annex B regions appears to be more robust to variations in the baseline scenario. Unsurprisingly, baseline scenarios with higher emissions lead to more carbon leakage since Annex B regions are forced to pay more carbon taxes for production. This increase cancels out roughly 25% of the additional gross reductions from the Annex-B countries' baseline scenario with the highest emissions. In percent terms, the carbon leakage is robust to changes in labor productivity but much less robust to changes in energy efficiency.

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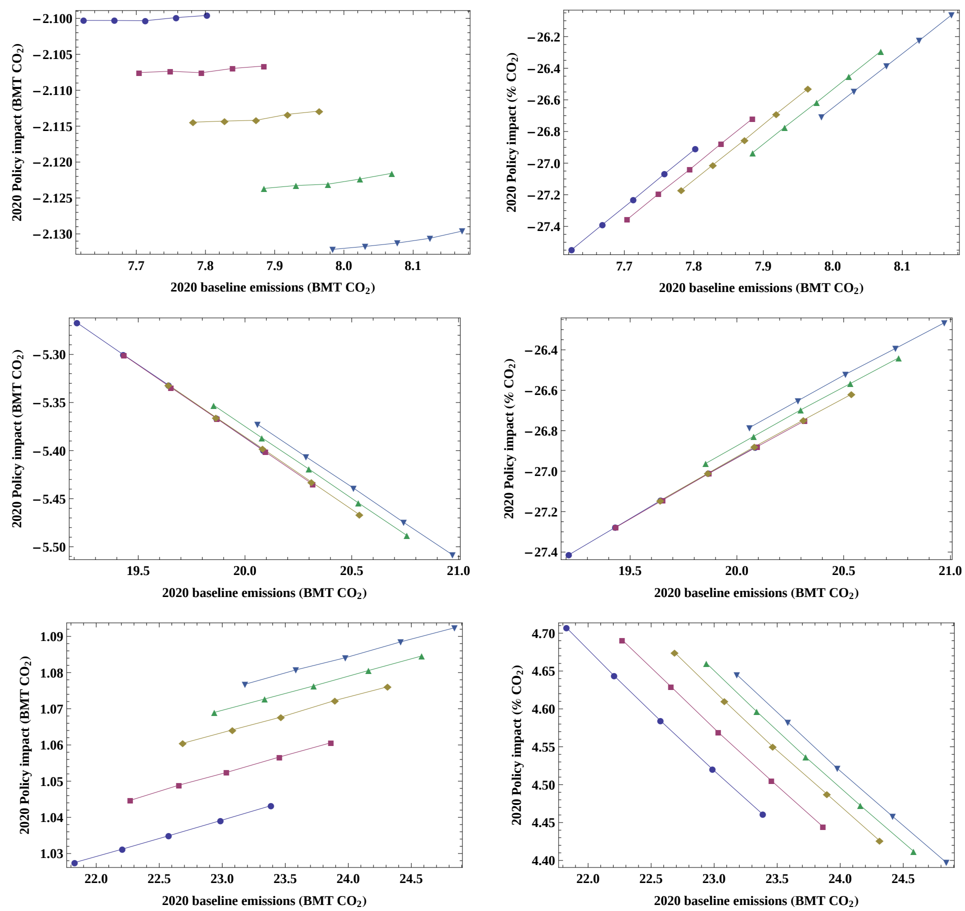


Figure 6: Policy implications of AB-105 scenario as measured against different baselines for gross emissions reductions (left) and percent of baseline (right). Measures shown for the USA (top), all Annex B countries (middle), and all non-Annex B countries (bottom).


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